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Communications Systems for Mobile Robotics

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ABSTRACT

Performance Confirmation is the activity by which the Yucca Mountain Project confirms that the engineered and natural containment barriers of this national nuclear waste repository are performing as predicted, so that an eventual decision to close the repository can be made. This activity involves systems that must be inspected and, in some cases, serviced by mobile robots. This paper discusses systems for underground mobile robot communications, including requirements, environments, options, issues, and down-select criteria. We reviewed a variety of systems, including Slotted Waveguide, Powerline Carrier, Leaky Feeder, Photonic Bandgap Fiber, Free-Space Optics, Millimeter Waves, Terahertz Systems, and RF Systems (including IEEE 802.11 a,b, and g, and Ultra-Wideband radio).

INTRODUCTION

The Yucca Mountain Project has been designated to be the United States' first national repository for long-term storage of high-level radioactive waste. Subject to NRC licensure, emplacement of sealed nuclear waste packages will begin in about 2010, inaugurating a period of inspection and monitoring of the performance of the engineered and natural barriers that provide a multi-layered containment of the wastes and their radiation. This so-called Performance Confirmation period may last from 50 to 100 years, as necessary to establish high confidence in the models that predict the performance of the repository and its elements over the approximately 10,000 years until the wastes have decayed to the level of radioactivity of the natural background. Once the performance of the repository is adequately confirmed, the repository will be sealed, and the Post-Closure period will begin.

Because the environment of the emplacement drifts containing the waste packages will become hostile, inspection of the emplacement drifts and items therein will be done by mobile robots. This paper describes options currently under consideration for communications with and/or among the mobile robots, which will be remotely controlled by human operators or autonomous.

Table 1 lists the environments within the repository in which the mobile robots will need to function. The Main Access Tunnel will be human accessible, and the mobile robot operators may work there, or on the earth's surface nearby the repository. The Emplacement Drifts will consist of a network of tunnels perpendicular to the Main Access Tunnel, all terminating in the Exhaust Main, which will provide an exit for the air used to ventilate the complex. In addition there will be two, unventilated, Thermally Accelerated Drifts, which will be used to test the performance of the repository under the Post-Closure conditions.

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Location	Rad/hr (□	Temperature (C)	Dia. (m)	Length (m)
Emplacement Drift	40—200	60—90	5.5	900
Thermally Accelerated Drift	40—200	140—180	5.5	600
Exhaust Main	1—2	< 60	7.62	7400

Table 1: Environments for YMP Mobile Robots. Radiation exposures are about 99% □and 1% neutrons.

Naturally, the primary foci of the Performance Confirmation activity are the Emplacement Drifts and the Thermally Accelerated Drifts. These will be partially obstructed by waste packages, as well as by ground support (Figure 1). We will therefore focus on mobile robot communications in these environments for most of this paper.

We were asked to consider a wide range of options, ranging from those available now to those in development. At varying levels of depth, we considered Slotted Waveguide, Powerline Carrier, Leaky Feeder, Fiber Optics, Free-Space Optics, Terahertz systems, Millimeter Wave systems, and Radio-Frequency (RF) systems, such as Ultra-Wideband Radio, IEEE 802.11-based systems, and 900 MHz systems. Each of these systems has advantages and disadvantages. The final selection will be made based on the results of ongoing investigations as well the requirements specific to the Yucca Mountain Project Performance Confirmation Program. This paper gives a preliminary down selection and directions for future work.

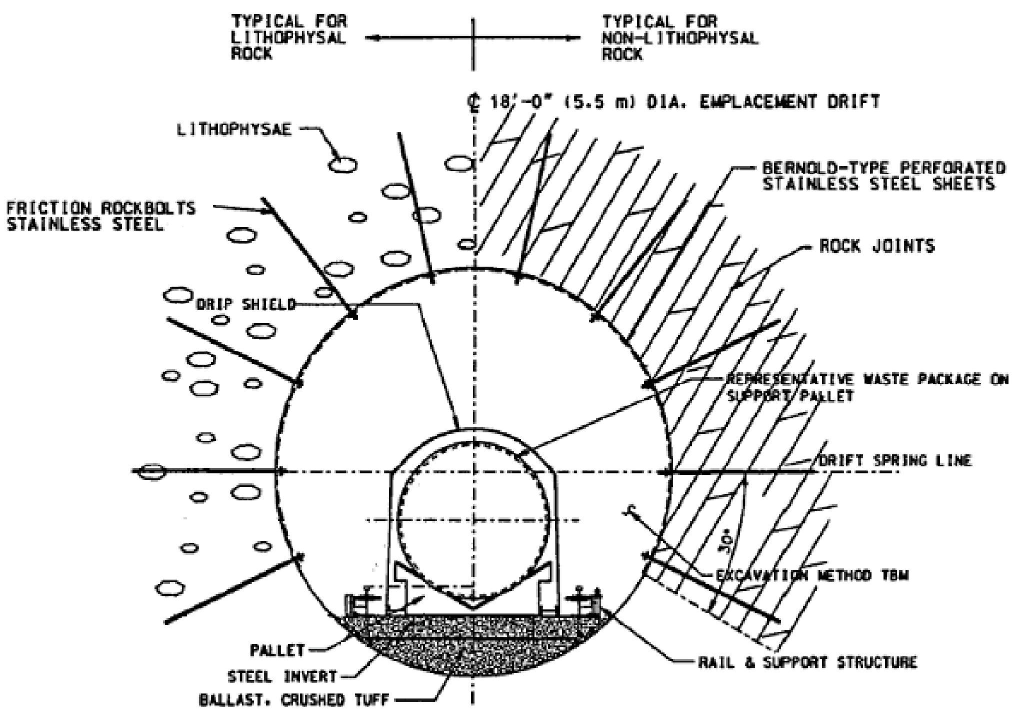

Figure 1. Emplacement drift cross section (5.5 m diameter). The drip shield will be present only in the Thermally Accelerated Drifts during the Performance Confirmation Period. They are planned for deployment in the Emplacement Drifts as part of the repository closure activity.

In our survey, we established several non-issues regarding possible communications systems for the mobile robots. All systems considered would draw less than 25 W power, with the self-contained (untethered) systems requiring less than 15 W. All systems will burden the yet-to-be-designed robot with less than 5 pounds, with most self-contained systems weighing well-less than one pound. All systems will require less than a cubic foot of space on the robot, most much less. Finally, all systems considered can nominally provide adequate bandwith.

The most stressing bandwidth requirement we identified was the need for full-motion video to monitor to help an operator control fine movements of the robot manipulator arm. We estimate that 2 channels of 14-bit color video at 30 frames per second, with wavelet based compression, will require about 4 Mb/s. Since all the communications systems we considered can provide more than 10 Mb/s, we believe that bandwidth *per se* is not an issue.

However, communications link availability and reliability are issues for systems that use propagation of signals (optical or RF) in the confined and partially obstructed space of the emplacement drifts and tunnels. Moreover, link endurance is an issue for all systems in that the thermal environment exceeds the specifications for circuitry using silicon-based semiconductors, and the gamma environment will damage both electronic and optical components. Finally, there are systems integration issues, in terms of how the communication system will interact with robot mobility, the composition of components (so as to avoid generation of low-level waste by neutron activation) and logistics (flow of failed components out of the project and replacement components into the project).

FIXED AND REMOVABLE INFRASTRUCTURE SYSTEMS

We first considered systems that rely on fixed infrastructure to provide a medium for communications, namely Slotted Waveguide, Powerline Carrier, and Leaky Feeder.

Slotted Waveguide has the advantage that it is being considered for the Emplacement Gantry robots that will transport the sealed waste packages and the pallets on which they rest from the Main Access Tunnel and deposit them in the Emplacement Drifts. These large robots, capable of carrying several tons, will be tethered, deriving electric power from an ungrounded third rail, and communications, as mentioned above, from a Slotted Waveguide system. Slotted Waveguide consists of a rectangular cross-section waveguide with a slot opened along its length, along which is drawn a probe antenna which protrudes into the waveguide channel. A coaxial cable (up to 5 m long for the manufacturer we considered) connects the probe antenna with the robot.

One could then imagine a small, agile Performance Confirmation robot connected by one tether to the Slotted Waveguide system, and connected by a second tether to the third rail power, both of which have been left in place by emplacement activity. However, two independent tethers may unduly constrain the mobility of the robot. Therefore, we also considered Powerline Carrier systems, which would enable the robot to use a single tether to the third rail for both power and communications. Powerline carrier systems range from capacities of 45 MB/s for the medium voltage (24 kV) commercial power distribution network to the 10—100 MB/s systems for use with 120 V residential wiring. These systems would require some adaptation to work with the 24 V system envisioned for the Performance Confirmation robots, which itself is a departure from the 600 V currently planned for the Emplacement Gantry.

Finally, among the fixed infrastructure systems we considered, is Leaky Feeder, which consists of a coaxial cable with the outer conductor made of wires spaced widely enough to allow the communications signal to “leak” out between them for a few meters. These systems have the advantage that they are currently in use to provide voice, data, and video communications in mines worldwide. In this case, power for the mobile robot would be self-contained, and the robot would operate untethered, relying on an RF antenna to provide a link to the cable, which would need to run the entire length of the Emplacement Drift, Exhaust Main, etc.

However, the mission of the Performance Confirmation robots requires them to be able to access and inspect the Emplacement Drifts even after events such as tunnel subsidence, rock falls or earthquakes (if they occur) should alter the geometry. These events are likely to disrupt fixed infrastructure such as a Slotted Waveguide system, or Powerline Carrier operating on the third rail. Moreover, Leaky Feeder systems rely on insulation to isolate the inner conductor from the outer conductor and the outer conductor, and the outer conductor from its environment. This insulation will eventually break down due to gamma irradiation, requiring that the entire infrastructure be replaced periodically, burdening the Performance Confirmation robots with additional tasking and dramatically increasing the cost of the Performance Confirmation activity due to the expense of first emplacing and then replacing the Leaky Feeder cables. (This last expense could perhaps be avoided by having the robots deploy a single Leaky Feeder cable temporarily as they access each drift, but the weight and volume of 1000 m of such cable would be prohibitive.)

Thus, however well-established fixed infrastructure systems may be in commercial mines, the peculiar requirements of the Yucca Mountain Project lead us to reject them except for temporary use to provide more time for an alternative system to be developed and deployed.

A possible alternative is to use a removable infrastructure system. The robots could carry a spool of optical fiber which they could unwind as they moved into a drift or tunnel, and rewind as they exited. If the fiber optic were to be made of Photonic Bandgap (or Photonic Crystal) material, with the light beam confined to a hollow air core, such a fiber would be more resistant to darkening caused by irradiation than the more common optical fiber, which relies on dopants to create a refractive index profile that confines the beam. A kilometer of fiber might weigh as little as a kilogram. We continue to consider this type of system as a possibility, even though it would generate extra requirements and activities for the robots to manage the fiber, to deal with fiber snags, and to be able to recover from loss of communications due to fiber breaks.

We also briefly considered wire-pair systems, but in the absence of specific designs and concepts of operations for the robots and manipulator arms, do not have confidence that the bandwidth will be sufficient over the distances required.

WIRELESS SYSTEMS

We next considered wireless systems, such as Free Space Optical, Millimeter Waves, Terahertz Systems, and, of course, RF systems such as IEEE 802.11 a,b, and g, Micro-power Impulse Radio (MIR, also known as Ultra-WideBand or UWB radio), and 900 MHz systems.

Free Space Optical Systems (FSO) have the advantage of excellent signal quality because the narrow beam does not interact appreciably with the tunnel walls. However, this same narrow beam is of too short a wavelength to diffract around obstructions, such as ground support ribs, and the waste packages themselves. We term the loss of Line-of-Sight (LOS) to be the link availability issue: the link is good, provided that it is available. Maintaining LOS generates additional requirements and tasking for the mobile robots, as does the necessity of recovering from interruption or loss of LOS, and re-acquiring and re-establishing the link. Nevertheless, because of the high quality and high bandwidth (Gb/s) of the links when available, we continue to consider FSO systems as an option for mobile robot communications.

Terahertz systems are subject to both the LOS considerations of FSO systems, as well as attenuation by the atmosphere in the tunnels and drifts. Millimeter wave systems are also subject to loss of LOS. Given that both Terahertz and millimeter wave systems will have lower bandwidth and be more expensive than FSO, we see little reason to devote the effort to pursue these options in preference to FSO or RF systems, which we consider next.

Radiofrequency (RF) systems employ wavelengths that are long enough to diffract around most obstacles, minimizing the requirements to maintain LOS, but these wavelengths are also long enough to interact with the surfaces of the tunnel walls, ground support, rails, and waste packages. This will generate multiple reflections of the original signal, which will interfere with each other causing multipath fading. Indeed, the problem of predicting the performance of RF systems in underground and other complex environments is unsolved, and the subject of ongoing investigation by a team led by one of the authors of this paper.[1,2,3,4]

Briefly, the electric and magnetic field potentials are expanded in eigenfunctions appropriate to the nominal tunnel geometry. Roughness is modeled as a statistical perturbation of the geometry, which is also expanded in eigenfunctions, so that the boundary conditions can be satisfied mode-by-mode. The end result is a transfer function that relates the power spectral density of the tunnel roughness to the statistical properties of the electromagnetic fields in the tunnel. We plan to validate this model with scaled experiments, and then to apply it to predicting the performance of RF systems in the Yucca Mountain Project.

Other means to compensate for multipath fading include the use of so-called “space diversity” which can be achieved by moving the robot until it is out of the region of destructive interference, or by having it carry two or more antennas and a circuit to combine their inputs. So-called “time-reversal” techniques (also a subject of ongoing investigation) can be used in which a pilot signal from the robot is used to compute how to pre-distort the signal from a phased array at a base station temporarily placed at the drift entrance. Finally, repeaters can be used to break the transmission path into shorter segments in which good propagation can be achieved. Such repeaters could be deployed and recovered by a single robot, or several robots could enter the drift together and act as repeaters for one another.

We continue to consider UWB systems (which are robust to multipath in many environments) and Radio-Frequency (RF) systems, such as Ultra-Wideband Radio, IEEE 802.11-based systems, and 900 MHz systems. All these systems require little power, and are lightweight, posing little burden on mobile robot operations. In particular, we are encouraged by an impromptu experiment performed by John Beesley, who asked a robot manufacturer to drive its remotely controlled device down an unobstructed tunnel in Yucca Mountain until it lost signal. The 900 MHz RF link, which carried control and video signals, was useable for a distance of 500 meters.

DOWN SELECTION CRITERIA AND FUTURE WORK

Perhaps the strongest criterion for down-selecting communications technology for the mobile robots is that the technology leave no additional material inside the emplacement drifts beyond that left by the emplacement activity itself. The reasons for this requirement are two-fold: first, the behavior of any material to be left in the drifts must be predicted by modeling for a period of 10,000 years and measured for a period of 50 to 100 years, and, second, any infrastructure introduced by the Performance Confirmation activity will dramatically increase the cost and scope of that activity.

Thus, Leaky Feeder is eliminated in the Emplacement and Thermally Accelerated Drifts, because the emplacement activity does not plan to use it there. Systems like Slotted Waveguide and Powerline Carrier are also eliminated, because the emplacement Activity may actually remove that infrastructure upon completion, and because even if it is left in place, changes in tunnel geometry due to seismicity, etc., may render those systems inoperable, necessitating an alternative backup system in any case.

The remaining candidates are temporarily emplaced (wound and unwound from a spools by the mobile robots) Photonic Crystal Fiber (also known as Photonic Bandgap Fiber), Free Space Optics, and RF systems. In order to select among these, experiments and systems engineering activities are planned. In particular, the thermal and radiation tolerance of these systems and components thereof will be tested and compared. It may be that no ideal system emerges from these tests, in which case we may plan to thermally insulate heat-sensitive system components (the duration of a given mission is likely to be about 8 hours), and to plan to discard and replace components as they are predicted to become unreliable due to radiation exposure.

We also plan to take RF units to the Yucca Mountain Project Experimental Science Facility (ESF, currently the only part of the facility that has been constructed) and perform basic “Can you hear me now?” tests, since complete characterization of the RF propagation environment in the facility is cost prohibitive. This activity will be coordinated with those parts of the emplacement activity currently working on the communication system for the transporter and gantry that will emplace the waste packages. Besides Slotted Waveguide, this activity is also contemplating IEEE 802.11 (a) and (g) systems to connect these mobile units to a Synchronous Optical Network (SONET) backbone running throughout the Main Access Tunnel and up to the surface. Thus, if the results of our experiments and theoretical modeling prove positive, both activities may converge on IEEE 802.11 type systems for mobile robot communications.

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